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PRESERVING SIGNIFICANT HISTORICAL STRUCTURES WITH THE HELP OF COMPUTATIONAL MECHANICS OF DISCONTINUA

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Abstract. Architectural and engineering geniuses of ancient times have left to the world an important heritage of stone, masonry and other structures ranging from temples, churches, mosques, pyramids to aqueducts, palaces, and dams. Preserving these for future generations is one of the more important challenges facing modern civilization. In some places vibrations from traffic can be a cause of gradual damage, which if not counteracted could result in eventual catastrophic collapse. More often than not, it is earthquakes that pose such a threat that catastrophic failure could occur. Other factors or combination of factors can also cause catastrophic distress to a structure (impacts, blasts, fire, lightening, etc.). Modern engineering design practices usually consider the so called ultimate limit states for a structure as a whole. By using the theory of probability for design parameters such as loads and material properties, one can arrive at the probability of a catastrophic failure of a structure given a particular event. The problem with applying these to significant historical structures is that the computational tools available are at times somewhat limited for ancient structure analyses purposes simply because of the specific and innovative ways the structures were built. In this paper, using the Los Alamos MUNROU package it is demonstrated that the combined finite discrete element method (FDEM) has some unique capabilities in modeling the ultimate limit state of historical buildings; each individual stone blocks or stone anchors could potentially be captured with accurate representation of frictional energy dissipation under transient dynamic loads. Our work here focuses on an initial cursory analysis of the potential earthquake threat posed to one of the most famous historical structures, the Santa Maria Del Fiore Dome in Florence.

1 ANCIENT STRUCTURES IN GENERAL

Modern structural engineering design codes are based on the ultimate limit state analysis often coupled with structural reliability analysis. As such, they are designed for modern materials and modern construction methods. Engineers and architects of ancient times tended to build their monuments from the locally available limestone or granite resources, while in other locations even soft sandstone was used. Where stone was not readily available, ancient builders used bricks. In all cases, either iron, timber, or lead were used to further strengthen the structure. Also, mortars ranging from bituminous mortar (used by Babylonians) to limestone-based mortar and even cement-based mortar (used by Romans) were utilized to keep the blocks together.

Ancient structures hundreds to thousands years old can be found in all parts of the world. As such, they have survived wars, extreme weather, earthquakes, floods, and many other natural and human-made disasters to such an extent that many wonder: How is this possible?

There are several reasons for this. The most obvious one is that time has served as a "natural" selection mechanism through which the weaker monuments have simply been eliminated and only the most robust ones have survived. But, there is another factor that has played an important role in preserving ancient monuments and it is the mastery of the building craft by its creators starting with Babylonians, Mayas, Egyptians, Romans and others. The builders had to use materials such as stones or bricks, which are durable in comparison to modern man-made materials, such as steel. In addition, they could not afford the luxury of tension bearing structural elements with few built-in redundancies, which characterize modern structures. As a result, the structures are in general dominated by compression stresses. When these stresses are coupled with dynamic loads they produce high energy absorption mechanisms for earthquakes or lightening loads, as the key energy dissipation mechanism is the friction. Unlike structural members loaded in tension, compression loaded structural members can absorb a much larger amount of energy before reaching the collapse point. The energy can be increased by few orders of magnitude when compared to permanent deforming of the material, which is dominant in modern structures. This is probably the most important reason why these monuments have survived for millennia.

However, modern civilization is putting new strains on historical structures, such as:

1. pollution,
2. climate change,
3. dynamic loads much greater in magnitude, such as blasts,
4. long lasting dynamic loads, such as urban traffic,
5. high impact loads, etc.

Thanks to the skills of their creators, ancient structures have survived all that nature threw at them, but they are unlikely to survive these new threats without an active helping hand from the same civilization that threatens them.

Preservation of architectural heritage in modern societies is considered a major issue since, in addition to their historical value, historical buildings significantly contribute to economy. Preserving historic constructions is therefore not only a cultural requirement but also an economic and developmental demand [1]. While the structural behavior of modern structures is a relatively simple task (thanks both to the presence of standard codes software and inherent literature), the prediction of the structural response of monumental buildings is a more challenging task. At first, each monumental building is “by definition” a unique building, characterized by its own history (often resulting in a composite mixture of added or substituted structural elements, strongly interacting [2], [3]). Moreover, the static and dynamic behavior of ancient buildings is normally too complicated to be interpreted by simple mechanical models and usually cannot be reduced to any standard structural scheme because of the uncertainties that affect both the structural behavior and the mechanical properties distribution.

The above considerations highlight the need for specific modeling, analysis and experimental strategies for each historic masonry structure. Engineers involved in the study of cultural heritage are required to have a particular care in the understanding of the historical process as modifications occurring through the building’s history produced several uncertainties in the model definition (geometry, materials, connections etc.). A correct structural evaluation must therefore be based on a deep knowledge of: (i) building history and evolution, (ii) geometry, (iii) structural details, (iv) cracking pattern and material damage map, (v) masonry construction technique and materials, (vi) material properties, (vii) global behavior.

Figure 1: The Cathedral of Santa Maria del Fiore and the Brunelleschi’s Dome.

In order to be able to preserve these structures, we have to understand the dynamic load bearing mechanisms, energy dissipation mechanisms and other mechanisms that help these structures survive, for instance, an earthquake, while modern buildings next to them collapse.

It is worth mentioning that using modern continuum based software packages for ancient structure analysis sometimes is not enough and can be misleading. A classic example is the modal analysis. Modal analysis is a great tool for modern structures. When employed in highly non-linear context of ancient structures dominated with friction based load resisting mechanisms, the obtained results do not even resemble the actual physics of the load bearing process and load bearing mechanisms become processes of dissipating energy received from the earthquake or blast.

2 THE BRUNELLESCHI'S DOME OF SANTA MARIA DEL FIORE

The construction of the Brunelleschi's Dome in Florence (Figure 1) started in 1420 and finished in 1434, under the design and the supervision of Filippo Brunelleschi. In 1415 he proposed an audacious self-supporting construction not requiring any scaffolding design for the Dome (scaffolds were always used to support the structure under construction in all the previous Roman and Gothic constructions). To date the Brunelleschi’s Dome, a double-shell masonry dome, remains one of the largest brick dome ever built in the world. Its global dimensions consist of an internal shell span of about 45 m, with a height of about 36 m.

From a structural point of view the Brunelleschi's Dome consists of two layers, an inner thick masonry dome spanning the diameter of the octahedral ring beam (the tambour, the structure beneath the Dome) and the external shell, whose function is to protect the previous one against the environmental loads. The inner layer (the structural one) has an even thickness (about 2.2 meter); the outer layer (the covering one) becomes gradually thinner from the base (where the thickness is about 80 cm) to the oculus (with a thickness of about 40 cm). These two layers are structurally connected by masonry ribs that starting from the octahedral tambour continues until the oculus. Because of both the magnificence of the construction and the “mystery” about the constructive system ideated by Brunelleschi, together with the presence of a complex and significant cracking pattern affecting the whole structure, the static behavior of the Brunelleschi’s Dome has attracted the attention of a plethora of researchers over the centuries. The interested reader can find a reconstruction of the history of the Brunelleschi’s Dome in a book by Giuseppe and Michele Fanelli [4].

The Cracking Pattern. From a merely structural point of view, one of the main aspects of the monument is the peculiar crack system affecting the Dome, Figure 2. With reference to this figure, it is worth mentioning that main cracks (those indicated as type A) pass through the two shells and in some points their width is of several centimeters.

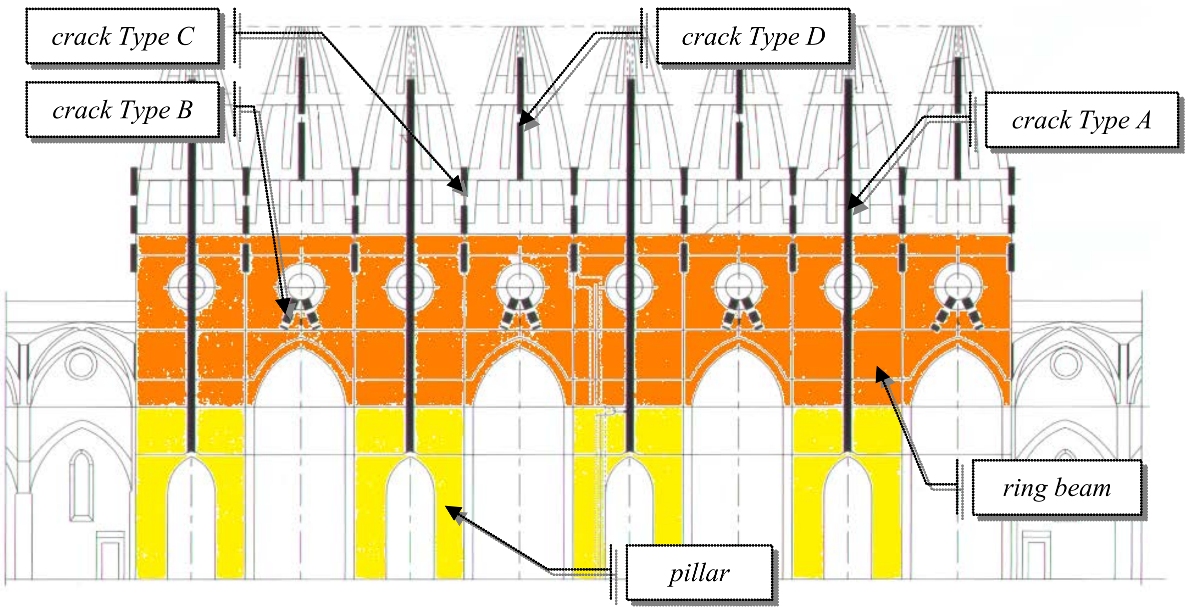

Figure 2: Internal view of the ring beam (and schematic representation of cracks).

The first documented historical information about the damage of the Brunelleschi's Dome was reported in 1639 by Gherardo Silvani, but these cracks were already present in previous periods as is shown in historical pictures and drawings. One of the first works on the description of the crack pattern was performed by the Jesuit Leonardo Ximenes. In his study, Ximenes makes a complete survey of the cracks describing 13 different crack typologies. This description is quite exhaustive and very useful as it allows, by comparison with the present crack, to follow the evolution of the cracking pattern over the centuries. More recent efforts describing the fully evolved crack pattern (as seen in Figure 2) can be found in Bartoli et al. [7] and Blasi [8].

3 THE FIRST NUMERICAL FE MODELS FOR THE BRUNELLESCHI'S DOME

The initial use of FE numerical models was to enhance understanding of the static behavior of the Dome and to examine the origin of the actual cracking pattern. The first numerical model of the Dome was built using by using a finite element code implemented at the ENEL-CRIS Research Centre in Milano. The authors, starting from a quarter of the Dome (and including the basement structures), investigated the effects of the thermal loads according to their yearly periodic variations [7] [8]. The superposition of the effects of the static loads and the thermal variations provided some hints on the origin of the present cracks and on the static performance of the cracked structure. Results of these investigations allowed modelers to exclude thermal variation and foundation settlement as the main causes for the initiation of the cracking pattern. At the end of nineties a numerical model was built with the finite element code FEMAS90. This model, took advantage of the results of a digital monitoring system installed by ISMES (Experimental Institute for Models and Structures) on the monument over a period of 6 years, allowed investigators to evaluate the effect of the periodic variations of the thermal loads on the crack openings [9].

4 THE LATEST FE MODEL FOR BRUNELLESCHI'S DOME

Based on a recent topographic survey of the Dome, a more complete numerical model of the Dome was built with the FE code ANSYS by using solid hexahedral elements to model all the geometrical components. The aim of this new modeling was to study the seismic vulnerability of the Dome [11].

In a first step the numerical model was built without the presence of the cracks (undamaged model). The model was used for geometric nonlinear step-by-step restart analyses that aimed to reproduce the constructive phases (first it considered the effects of the main pillar, next the arches, etc.) and to assess the likely time evolution of the cracks. Starting from the results of the undamaged model a first improvement was made by introducing nonlinear contact elements along the areas where non-admissible tensile stresses arises. It became apparent when taking into account the limited information on material properties, that a discrete crack modeling technique was preferred over a smeared crack approach.

Subsequently the FE model was used to assess the seismic behavior of the Dome by means of a simple pushover analyses: the effects of the seismic loads were evaluated through the application of two systems of orthogonal forces lying in the horizontal plane. These forces, which are not acting simultaneously, are determined taking into account two different load distributions (that could be considered as two limit states for the Dome capacity): 1) the first one was directly proportional to the masses (uniform); 2) the second one was assumed proportional to the product of the masses times the displacements of the corresponding Dome modal shape.

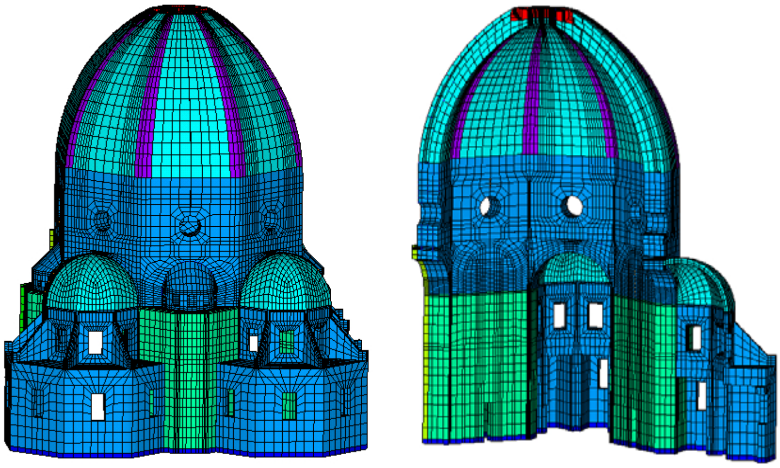

Figure 3: The new FE model: outer (left) and inner (right) view.

For the sake of brevity only the results obtained with the analysis in the North-South (Y direction, Figure 4) for the uniform loading will be described herein (due to the radial symmetry, the behavior in East-West direction is quite similar although not identical, due to the presence of the main nave). A general sketch of the seismic behavior is shown in Figure 4. As the load is acting in the +Y direction, it is possible to observe that an increase in the crack opening arises in webs #6 and #8, with a corresponding crack closure in webs #2 and #4. The cracks in the webs in the direction of seismic forces show a trend to close, while the cracks in the opposite webs tend to widen themselves. The crack opening on the webs, due to the seismic load, initiates a Type A crack propagation towards the top level of the Dome (the oculus).

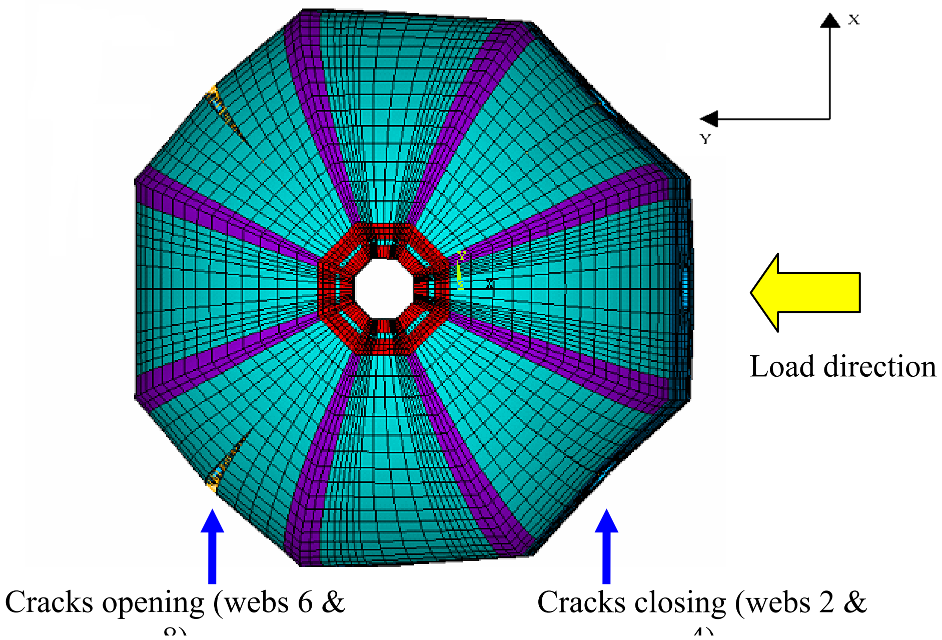

Figure 4: Webs cracks behavior under seismic load.

Figure 5 illustrates the numerical collapse configuration of the Dome. It should be noted that the more recent FE works intuitively pinpointed that that a more comprehensive approach is needed to truly understand how kinematic effects can produce such a catastrophic collapse.

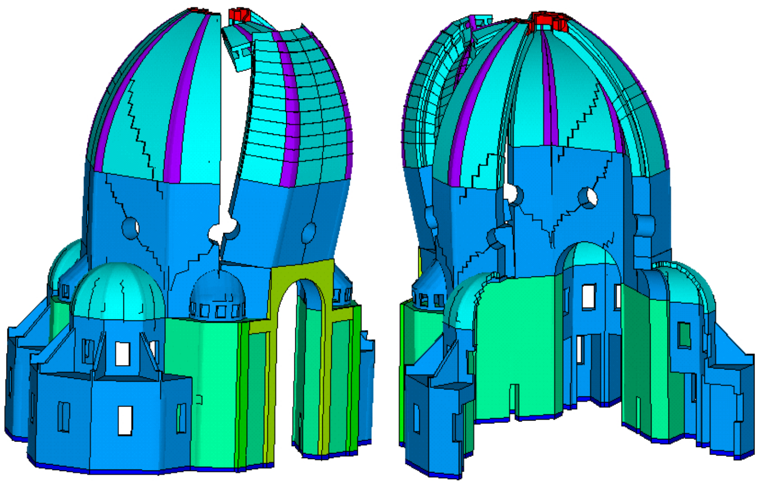

Figure 5: Collapse configuration: global view (enhanced displacements).

5 EXPLORATORY FDEM SIMULATION USING MUNROU

In recent years at Los Alamos National Laboratory, the FDEM and computational mechanics of discontinua have been brought to a new level through the development of a "state of the art" next generation of computer software called MUNROU. In this work, MUNROU has been, for the first time, employed to analyze a portion of a full scale ancient building, i.e. the Dome of the Santa Maria del Fiore Cathedral.

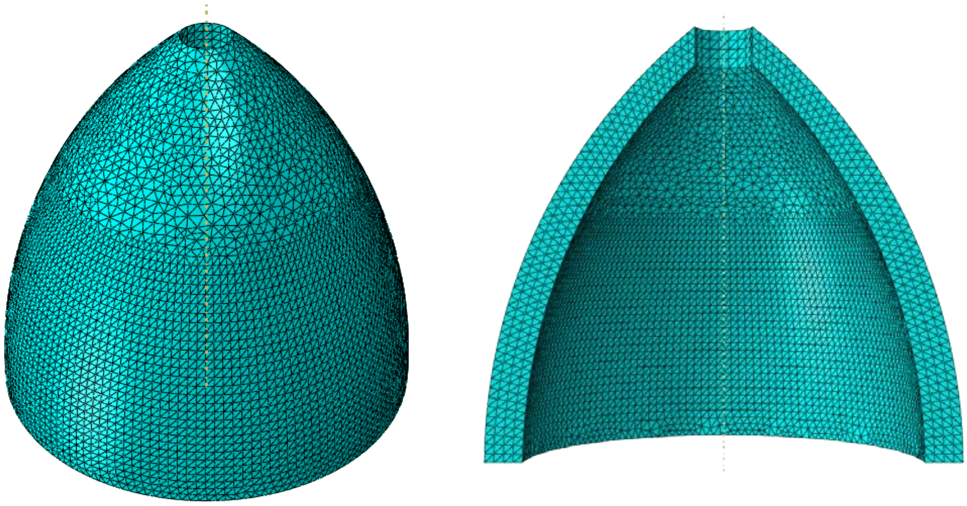

Figure 6: Two different views of the FDEM model of the top part of the cupola.

The FDEM Model. The exploratory numerical model for the dome is shown in Figure 6 [12]. Even though the FDEM model of the dome is axially-symmetric (unlike the real dome, which has eight webs, see Figure 1 and Figure 4), the meridian curve of the model of the dome resembles that of the Brunelleschi's dome. It is worth noting that in this numerical model there are no pre-existing cracks, i.e. the dome is initially intact. The mesh was created using the Cubit toolkit [13] and it comprises of around 150,000 solid 3D finite elements. The dome was subjected to an earthquake-like horizontal shaking load.

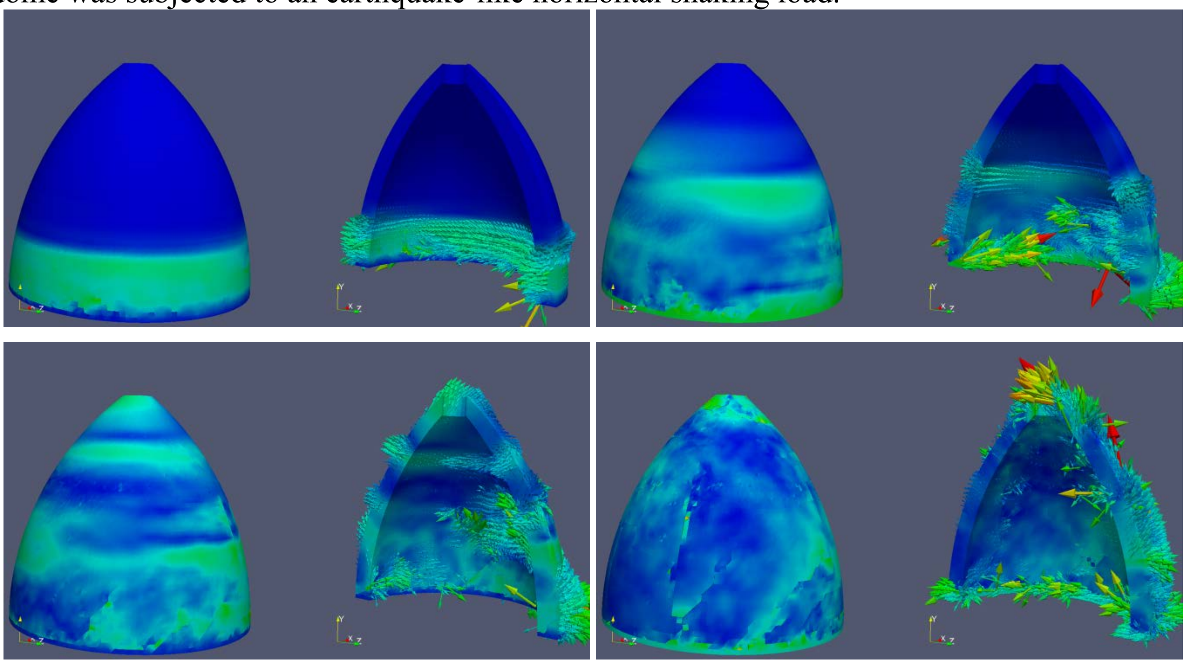

Figure 7: Initial stress wave propagation through the dome.

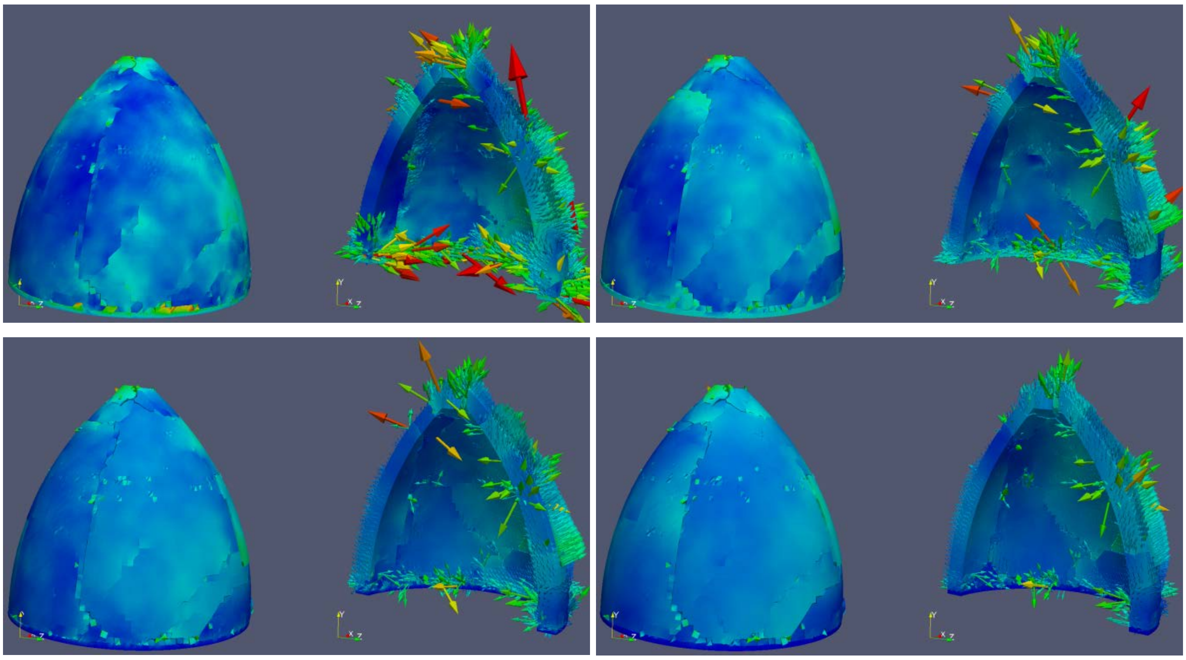

Figure 8: Later stages of stress wave propagation, including fracture inside the dome.

2 THE RESULTS

The obtained initial stress wave propagation in the dome, together with the velocity field, is shown in Figure 7. Later stages of the wave propagation along with the resultant fracture pattern are shown in Figure 8.

Obtained Fracture Patterns. The zoomed in view of the fracture patterns is shown in Figure 9. A further detailed view is shown in Figure 10. It is important to note that the dome has survived the load, despite the development of an extensive fracture map, which is likely to close after the load and even has the potential to "heal" through watering and cementation processes. In other words, the dome may partially "recover" some of its strength for the next earthquake assault in, say 100 years.

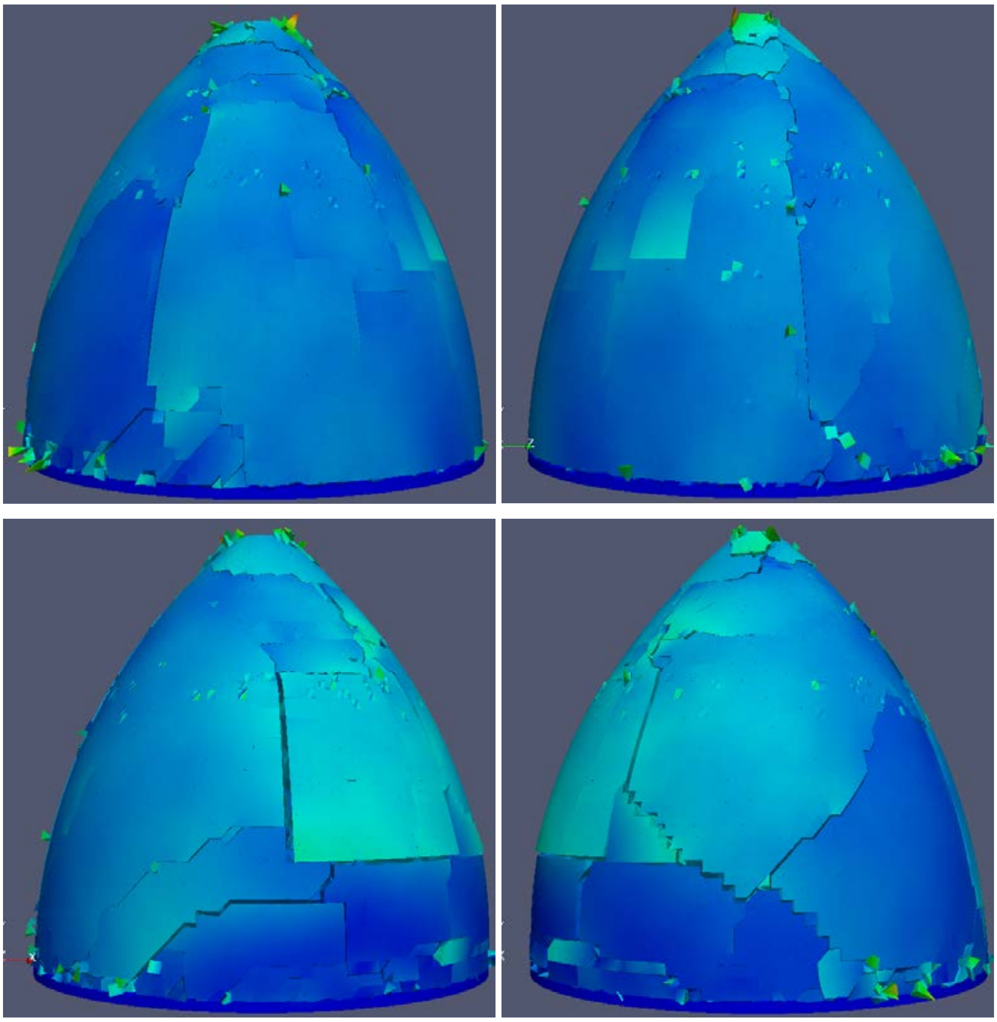

Figure 9: FDEM Simulation results showing the final state of fractures on the dome looking at it from the outside (enhanced displacements).

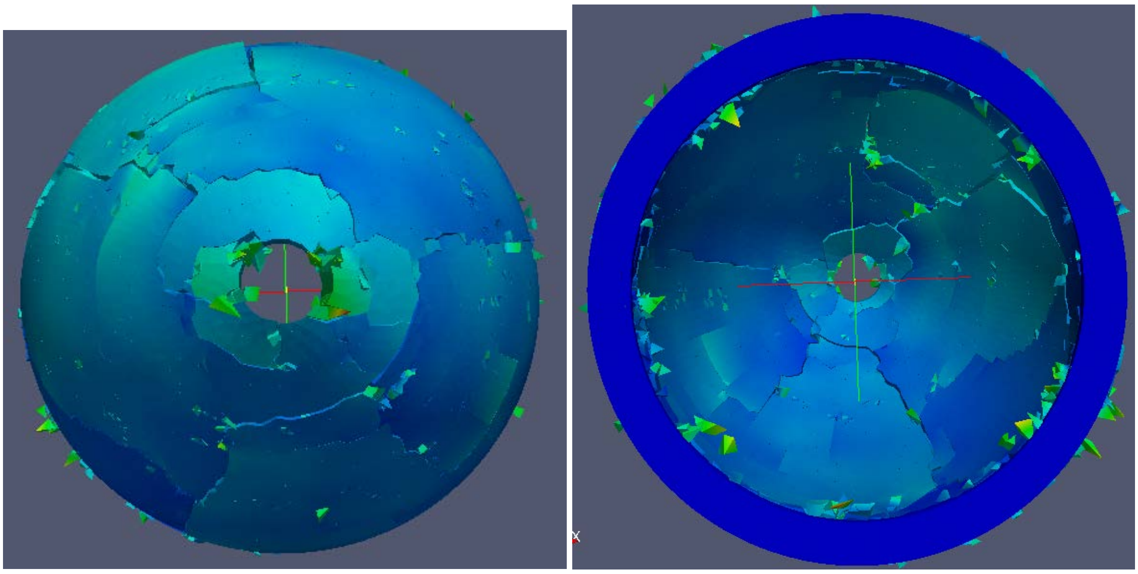

Figure 10: FDEM Simulation results showing the final state of fractures on the dome both from the top and from the bottom.

5 CONCLUSIONS

The exploratory results shown in this paper show the unique analysis capabilities that the FDEM can bring to engineers and preservationists as they battle the elements of time and nature. The cursory results obtained are intended only for demonstration purposes but they do show that now is the time to employ computational and theoretical approaches that employ advanced discontinua-based software tools. That stated, much work needs to be done before anybody can claim to model the collapse of such a complex structure accurately. These include material modeling, multiscaling analysis, benchmarking and validation efforts and many other aspects. As for the FDEM approach, it will benefit from tailor-made experimental approaches that would both validate and guide computational developments. The cause is a noble one and it requires international collaboration, as well as funding.

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